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MEASUREMENTS OF THE IRON-GROUP ABUNDANCE IN ENERGETIC SOLAR PARTICLES

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ABSTRACT

The abundance of iron-group nuclei in the energetic solar particles was measured twice in the 1971 January 24 event and once in the 1971 September 2 event. Including earlier results from the 1966 September 2 event, the experimental series being discussed in this article has found the iron-group abundance to be in the range from 3–6 percent of the oxygen nuclei in the energy interval from 21 to 50 MeV per nucleon, in those events where the iron-group abundance could be measured. Iron-nuclei have a different charge-to-mass ratio from that of the C, N, O nuclei, so small variations in the Fe abundance in solar particles are not unexpected due to rigidity-dependent propagation effects and possibly rigidity-dependent acceleration. In the three exposures where the statistics were adequate to construct an energy spectrum, the iron-group nuclei were seen to have an energy per nucleon spectrum similar to that of the C, N, O nuclei; however, the energy per nucleon range was limited. The abundance for the iron-group nuclei mentioned above is consistent with the present solar spectroscopic abundance estimates.

Subject headings: abundances, cosmic-ray — abundances, solar

I. INTRODUCTION

Continued studies of energetic solar particles emitted in conjunction with large solar flares have been conducted using nuclear emulsions carried aboard sounding rockets flown from Fort Churchill, Canada. Abundance determinations of the iron-group nuclei (defined here as charges 24 to 28, but presumably predominantly 26) relative to oxygen nuclei have been made in three separate solar-particle events, and significant upper limits for the iron-group nuclei exist in two other events. Although the Sun is a frequent emitter of energetic particles, nuclei with charges greater than 2 are relatively rare, as expected (e.g., Biswas and Fichtel 1965), and nuclei of the iron-group were not seen until the 1966 September 2 event (Bertsch, Fichtel, and Reames 1969). Subsequently, they have been detected several times (Price *et al.* 1971; Fleischer, Hart, and Comstock 1971; Crozaz and Walker 1971; Crawford, Price, and Sullivan 1972; Bertsch *et al.* 1971; Teegarden, McDonald, and von Rosenvinge 1972; Mogro-Campero and Simpson 1972*a*), although it has not always been possible to relate their abundance to other species in a very direct way. In this paper, the final results from measurements on the iron-group nuclei detected in the 1971 January 24 and the 1971 September 2 events will be reported and discussed together with the other results on iron-group solar particles.

The abundance of iron in the Sun as deduced from spectroscopic measurements is presently the subject of a controversy involving differences of more than an order of magnitude. Therefore, the abundance of the iron-group nuclei in solar cosmic rays is of particular interest, especially if the abundance there can be related to that of the Sun. The relationship between the two Fe abundances—i.e., that of the Sun and that of the energetic solar particles—is not completely straightforward, however, in part because Fe nuclei have a different charge-to-mass ratio from C, O, Ne, Si and other nuclei with which its abundance can be compared. This problem will be discussed later in the paper.

II. EXPERIMENT DESCRIPTION

The SPICE (Solar Particle Intensity and Composition Experiment) payloads and their Nike-Apache vehicles are kept on standby at the Fort Churchill Research Range in Manitoba, Canada, and fired when it is determined that an event of interest is in progress. Each payload has two nuclear emulsion stacks consisting of 24 pellicles with lateral dimensions 6.4×7.1 cm. A thin cover of stainless steel, having a total thickness equivalent to 72 μ of emulsion, separates the outermost pellicle from the particle radiation. This first pellicle is 200 μ thick. It is followed by three 300-μ and approximately twenty 600-μ pellicles. Experience has shown that this arrangement of thicknesses is advantageous since the high density of solar proton tracks in the outer pellicles of the stack makes it difficult to analyze tracks in a 600-μ plate. The two stacks have different sensitivities: one is composed of Ilford K.5 emulsions sensitive to minimum ionizing events, and the other of Ilford K.2 emulsions sensitive to protons of energy less than 40 MeV.

During the flight, the nose-cone of the payload is opened while the payload is above about 60 km, yielding an exposure time of 245 s. By means of spin stabilization, the emulsion detectors are held in a vertical plane. A total useful exposure of about 1.5×10^4 cm^2 sterad^{-1} s^{-1} is obtained.

In order to identify the iron nuclei, the surface of the top 200-μ plate was scanned to locate the tracks of heavy nuclei with at least 78 μ of projected length and dip angles between 10° and 60°. Tracks formed by iron-group nuclei were separated from tracks of lower charged nuclei with the aid of a digitized-television-microscope system operating on-line to a computer. The basic measurement is the total opacity per unit length of track, which is a measure of the rate of energy loss per unit length. The data are recorded at selected depths in the nuclear emulsion to avoid depth effects due to any variations in development or light illumination. The total opacity per unit length, corrected for dip angle, is then plotted against the residual range of the particle track to separate the iron-group nuclei from the others. More details on the digitized-television-microscope system and its use are given by Ehrmann and Reames (1969).

In addition to the charge-identifying measurements just described, the charge of each particle under consideration was also determined with a second estimate of the rate of energy loss. In most cases the measurement made was a delta-ray count, although in one sample a track-width measurement was made. The agreement between the two methods of charge identification was excellent; the few tracks for which discrepancies did exist could affect the Fe abundance quoted by no more than one part in 20, even if all the wrong choices were made.

Information on the C, N, O nuclei was obtained by scanning the outer surface of the nuclear emulsions and using conventional measurement techniques described in previous articles (e.g., Bertsch *et al.* 1971). This latter article also describes the approach to the remainder of the data analysis, so it will not be repeated here.

III. RESULTS

The first event in which iron-group nuclei were detected and compared to the C, N, O group was the 1966 September event (Bertsch *et al.* 1969)—the first event also in which the improved sounding rocket payloads, permitting the observation of lower energy particles, were used. As mentioned in the introduction, Fe has been seen recently by several groups. These results will be discussed after the presentation of the results to date from the SPICE experiment series being discussed here. With regard to these measurements, the 1971 January 24 and 1971 September 2 events are the second and third events in which iron-group nuclei have been detected, and in which the flux of iron-group nuclei can be compared directly to the abundance of C, N, O nuclei in the same energy-per-nucleon interval.

Figure 1 shows the differential energy-per-nucleon spectra of the C, N, O and the iron-group nuclei that have been obtained from three flights into two particle events. In the third event, 1971 September 2, the number of detected iron-group nuclei was too small to permit construction of a spectrum, although an abundance relative to oxygen was determined in the same energy-per-nucleon interval. In each of the three measurements, the C, N, O spectra and the iron spectra appear to have similar shapes, although the energy-per-nucleon spectral range of the iron-group nuclei is small. The figures do show, however, that the Fe data agree with the curve obtained by multiplying the C, N, O nuclei energy-per-nucleon spectrum by the ratio of the C, N, O and iron-group nuclei for the particular event.

We wish to call particular attention to the 1966 September 2 result. The revised ratio reported here based on detailed measurements is higher than reported previously (Bertsch *et al.* 1969). The change is due primarily to an improper scanning threshold for the preliminary work, although increased statistics contributed also. The problem relates only to the Fe nuclei scan and only to the 1966 September 2 event.

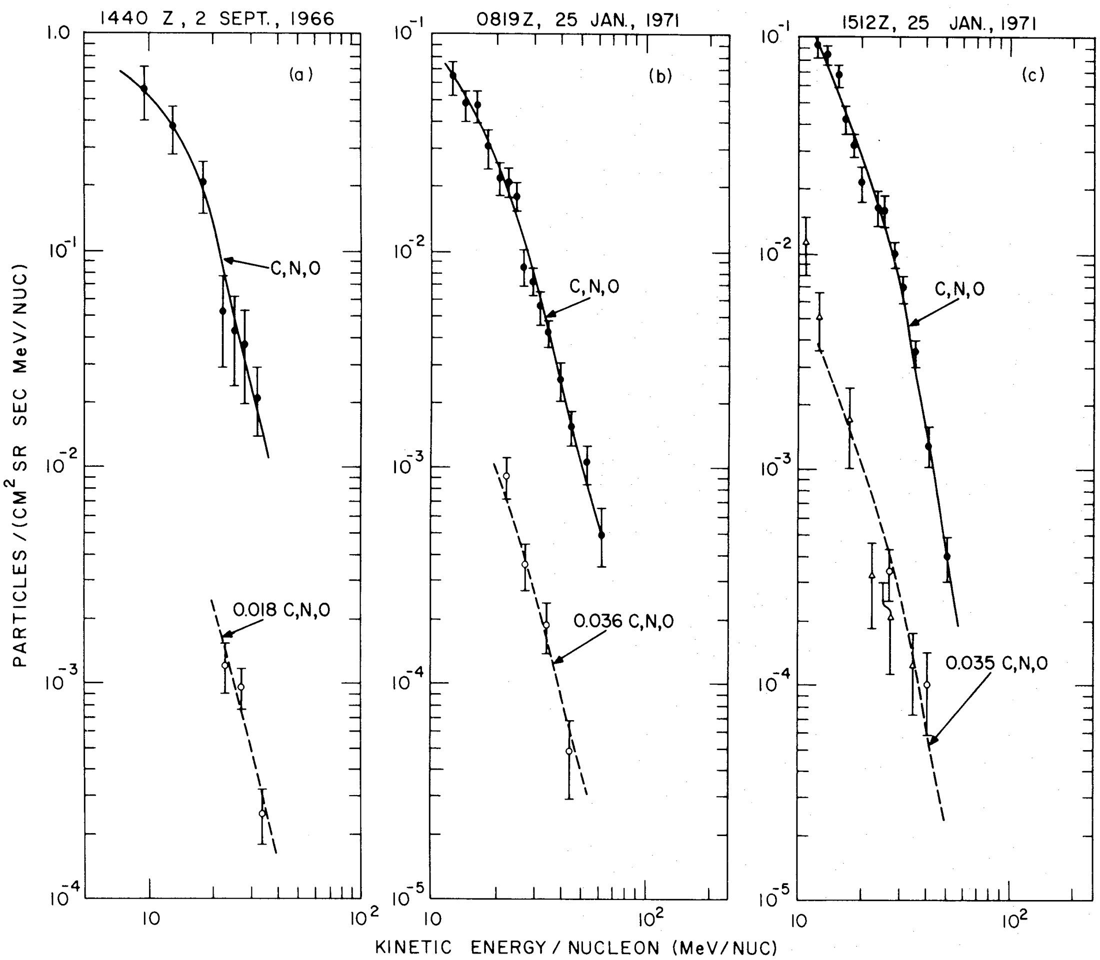

FIG. 1.—Differential energy/nucleon spectra for C, N, O nuclei (*solid circles*) and for iron-group nuclei (*open circles*) obtained with nuclear emulsions on three sounding-rocket flights. Solid curves are fitted to the C, N, O spectral data, and dashed curves are obtained by renormalizing the C, N, O curves to the iron-group data using the factors indicated. In (*c*) the iron-group spectral points of Crawford *et al.* (1972) obtained with plastic detectors on the same flight are shown (*open triangles*) for comparison.

TABLE 1

SUMMARY OF IRON GROUP MEASUREMENTS

DATE AND TIME OF MEASUREMENT		Fe/O IN %	ENERGY INTERVAL	NUMBER OF Fe GROUP NUCLEI DETECTED
NOV. 12, 1960	1840 UT	≤ 5*	77–150 MeV/NUC	0
SEPT. 2, 1966	1443 UT	3.1 ± 1.0	21–40 MeV/NUC	66
APRIL 12, 1969	2319 UT	≤ 5*	21–50 MeV/NUC	0
JAN. 25, 1971	0819 UT	6.3 ± 1.4	21–50 MeV/NUC	70
	1512 UT	6.0 ± 1.5	21–50 MeV/NUC	22
SEPT. 2, 1971	0758 UT	5.9 ± 1.8	21–50 MeV/NUC	14

*95% CONFIDENCE UPPER LIMIT

Table 1 summarizes the Fe-group abundance measurements relative to oxygen obtained thus far in the SPICE experiment series. Note that conversion from the C, N, O nuclei to just oxygen introduces a factor of 1.75, based on the observed (C, N, O)/oxygen ratio.

Of the two upper limits shown in table 1, one is related to the 1969 April 12 solar-particle event which is the only event using the new payload series where iron was not found. For the events before 1966 a different type of rocket payload was used and the low-energy threshold was much higher. Because of the steep energy-per-nucleon spectra, there were generally not enough particles to measure the Fe nuclei flux or set an upper limit of any significance. The one exception was an exposure obtained near maximum intensity of the relevant energy-per-nucleon interval in the 1960 November 12 event. This result is shown in table 1. In all other events, the number of oxygen nuclei measured in the iron-group energy interval was small and no iron-group nuclei were found; so, the upper limits are much higher than those given in table 1.

The data in table 1 suggest that the iron-group abundance relative to O may vary slightly from event to event. On the low side, there are two events with a 95 percent confidence upper limit of 5 percent for the iron-to-oxygen ratio, as well as the 1966 September value of 3 percent. These can be compared to the 1971 January measurements of about 6 percent. A small variation in the iron abundance is not surprising and is presumed to be the result of the fact that iron nuclei have a charge-to-mass ratio about 7 percent less than the constant charge-to-mass ratio of the lighter, even-charged nuclei. Hence, slightly different acceleration and propagation effects would be expected, since both may be rigidity dependent. These effects have been mentioned previously with regard to the Fe abundance in solar cosmic rays (Bertsch *et al.* 1969). The variation in the ratio due to the propagation effect is probably no more than a factor of 2, and probably much less. There appears to be no certain way of estimating theoretically the bias in the ratio introduced by rigidity effects in the accelerating process, if any, since the specific acceleration process for solar particles is not known.

Other results on the iron-group nuclei will now be summarized. Fleischer *et al.* (1971) measured the energy spectrum of iron-group nuclei from solar cosmic rays impinging on an optical filter of the *Surveyor 3* spacecraft for 2.6 years prior to its return by the *Apollo 12* astronauts on 1969 November 20. They deduced an E^{-3} differential spectrum from 1 to 100 MeV per nucleon, but had no direct means of comparing the iron-group nuclei with other species. Price *et al.* (1971) used both the *Surveyor-3* camera lens and a piece of the *Apollo 12* spacecraft window and deduced a similar Fe spectrum. These latter authors attempted to compare their results to the integrated He flux from other data. They deduced an Fe abundance in the range 6–10

MeV per nucleon that was about a factor of 3 higher than the larger values reported in this paper. A factor of 3 is probably within the uncertainties in this difficult comparison of two different experimental results on steep energy spectra at different points in space where the fluxes could be different due to geomagnetic effects and where different instruments not calibrated together are used. It should also be noted that the energy-per-nucleon interval is lower than those for the results being reported in this paper. Crozaz and Walker (1971) have shown that the *Surveyor-3* results are consistent with lunar rock results, implying that the rate of solar-particle production has been the same on the average for a very long period.

Crawford *et al.* (1972) measured the energy-per-nucleon spectra of iron-group nuclei using plastic detectors flown aboard the second of the two SPICE sounding rocket shots in the 1971 January 24 event. The measured energy-per-nucleon spectra in the same energy-per-nucleon interval as that of the present experiment agree within the uncertainties.

Teegarden *et al.* (1972) flew a low-energy solid-state detector telescope on IMP-VI. To date, they have measurements of solar-particle composition in two events. Relative to oxygen, they measure an iron-group abundance of 3 percent based on about 30 detected nuclei in the 1971 September 1 event consistent within uncertainties with the result given in table 1. When comparing the IMP-VI results with the SPICE measurements, it should be noted that the satellite experiment integrates over the whole event while the sounding-rocket exposure is only 245 seconds in duration. Small time variations in the abundance ratio Fe/O are expected due to the rigidity dependence of solar-particle propagation. Teegarden *et al.* (1972) observed an iron-to-oxygen ratio of 0.17 ± 0.10 in the 1971 April event, based on three iron-group nuclei.

The one result which is apparently markedly different from the values reported here and mentioned above is related to data from the OGO-5 satellite experiment of Mogro-Campero and Simpson (1972*a*, *b*). They deduce an average Fe/O value of 0.79 ± 0.29 for many events from 1968 to 1971 as well as a variation in the value from event to event.

IV. DISCUSSION

Before proceeding with the Fe discussion, a brief review of a few features of the solar-particle composition will be given. One aspect of the energetic solar particle composition, which has been seen in an examination of the experimental results of the sounding-rocket nuclear emulsion series, is the apparent constancy of the relative abundances of particles with the same charge-to-mass ratio within experimental errors in all events where a comparison could be made at energies where the nuclei are fully ionized (e.g., Biswas and Fichtel 1965; Fichtel 1971; Bertsch *et al.* 1972). This constancy prevails within the 15–20 percent statistical uncertainty of the individual measurements despite large variations in the intensity, changes in the spectral shape, and large differences in the proton-to-helium ratio. The weighted average of the He/M ratio is 58 ± 5. The energy region spanned by the measurements is from 10 to 200 MeV per nucleon, although most measurements are either in the range of 42–95 or 12–50 MeV per nucleon. Figure 2 summarizes the abundance measurements made with the sounding-rocket nuclear emulsion experiment series, and compares them with the abundances measured in the photosphere and corona by spectroscopic techniques. The photospheric and coronal abundances shown in figure 2 are those adopted by Withbroe (1971). Note the good agreement of these cosmic-ray measurements with solar spectroscopic measurements where comparisons are possible.

With regard to comparisons to other solar-particle measurements there is generally good agreement for C, N, O, and Ne. For Mg and heavier nuclei, Mogro-Campero and Simpson (1972*a*, *b*) obtain generally higher results. Teegarden *et al.* (1972) differ from the values reported here for Mg and Si, but agree with the values or limits for

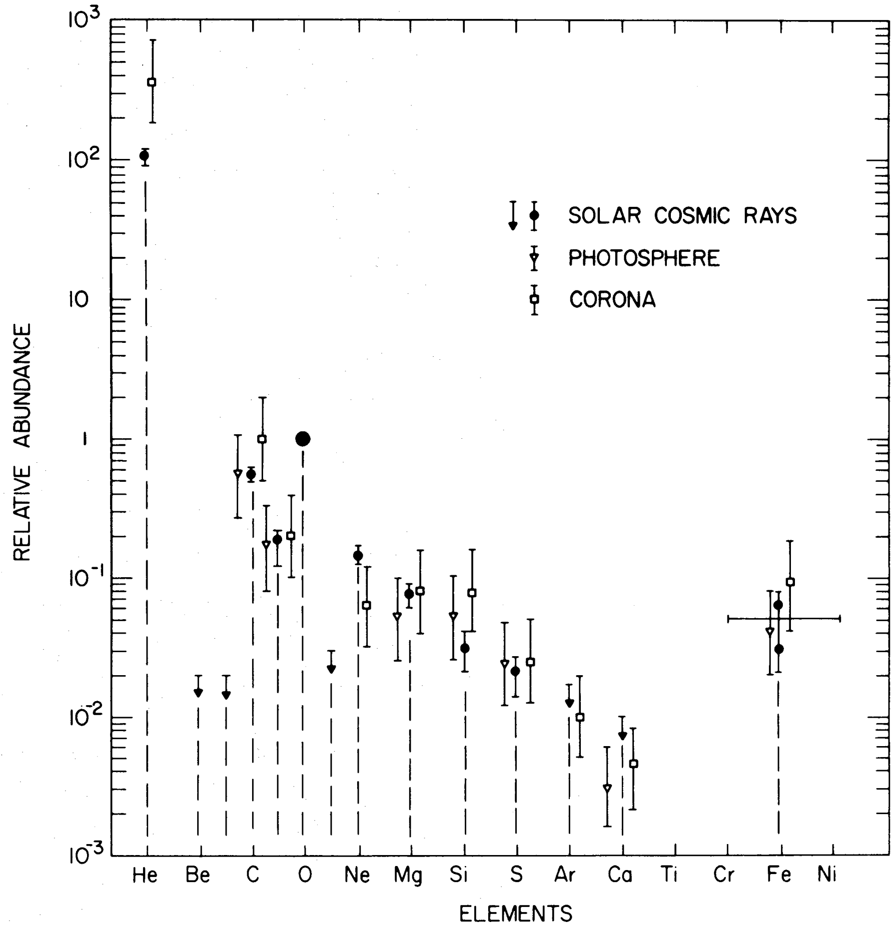

FIG. 2.—Abundances relative to oxygen for energetic solar cosmic rays and from spectroscopic measurements of the solar photosphere and corona. Data on solar-particle composition quoted in the above figure come from the nuclear emulsion sounding-rocket program only as discussed in the text. The data for Be through Ca are summarized from Fichtel and Guss (1961), Biswas *et al.* (1962, 1963), Bertsch *et al.* (1972), additional work on the 1960 November 12 event, and the present work on the 1971 January 24 event. The data on He are summarized from the above references and Biswas *et al.* (1966). The data on Fe are from the present work. Photospheric and coronal abundances are those adopted by Withbroe (1971), and their error bars reflect the precision suggested by that author.

In the cosmic-ray measurements, the ratio between a given species and oxygen is calculated for the same energy-per-nucleon threshold, which varies with charge ranging from typical values of 8 MeV per nucleon for carbon to 24 MeV per nucleon for iron in the later measurements. Measurements prior to 1966 are based on higher-energy regions typically 42 MeV per nucleon for carbon to 80 MeV per nucleon for iron.

S, Ar, Ca, and Fe. Using iron-group abundances measured in the same sounding-rocket flight as normalization, the results of Crawford *et al.* (1972) agree within errors with abundance results shown here in figure 2 for O, Ne, Mg, S, Ar, Ca, and differ for Mg. There are also some differences in the He abundance reported, but this question will be addressed in a separate paper.

Assuming that the slightly different charge-to-mass ratio for Fe or other effects do not affect the abundance in a significant way during the acceleration or propagation phase as discussed earlier, the iron-group abundance in solar cosmic rays in the energy-per-nucleon region where Fe is nearly fully ionized seems to be generally in agreement with the more recent spectroscopic estimates of several percent of the oxygen abundance; although there is one experiment (Mogro-Campero and Simpson 1972*a*) that suggests that the iron-group abundance in solar cosmic rays is nearly equal to that of oxygen. There also appears to be a difference from the several-percent figure for Fe relative to O at very low energies (Price *et al.* 1971; Mogro-Campero and Simpson 1972*b*), but here (a few MeV per nucleon or less) the Fe nuclei may be far from fully ionized and serious propagation effects might come into the picture. Thus, the question of the Fe abundance in the energetic solar particles following solar particle flares is still far from answered, but in the energy-per-nucleon range above about 10 MeV per nucleon an Fe/O ratio in the range of several hundredths seem to be developing, at least as the most common value for large solar-particle events. More experimental results are clearly desired, however.

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